Atom Optics: Using Light to Position Atoms

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1 Introduction

In most conventional lithography techniques, a light-sensitive resist is used to transfer a pattern from a mask to a substrate. The process is massively parallel because one mask can be used to expose millions of features at the same time. The minimum size of the features which can be created with conventional lithography is of the order of half the wavelength of the light being used. Extensions of optical lithographic techniques, involving deep ultraviolet light or x-rays, are predicted to reach a limit of approximately 0.1 μm.[1] Electron beams can write extremely narrow features, but in conventional electron beam systems the writing process is serial, so large complicated patterns take a very long time to write. Thus, there is great interest in developing parallel techniques of creating nanometer-scale features. The new field of atom optics offers various massively parallel fabrication techniques which hold the promise of creating nanometer-scale features with good contrast and resolution. These advantages are augmented by the "direct-write" nature of atom optical fabrication, that is, structures can be grown directly on a substrate without the intermediate process steps in-

volved with using a resist.

Figure 1 shows a number of conceptual ways in which atom optics can be used to fabricate nanostructures. Generally, a beam of atoms propagates toward a substrate, and a pattern of light beams is used to manipulate the atoms, controlling their deposition. The light can deflect the atoms from parts of the substrate, a process which uses the light as a mask or a stencil for the atoms, as shown in Fig. 1a. The light can also be used as a lens to focus atoms onto particular areas of the substrate, producing high flux of atoms at the focal points of the lens, and diminished or zero flux over the remaining areas, as shown in Fig. 1b. In addition, light can serve as a waveguide which confines atoms in narrow spatial regions, so that the atoms are delivered to the substrate in only narrow selected regions. Each waveguide is analogous to an optical fiber, which contains light within the core and can be used to deliver the light to a particular chosen area of a substrate. The complete atom optics process is then equivalent to a bundle of optical fibers which can be used to simultaneously deliver small points of atoms to many narrowly confined regions of a substrate, as shown in Fig. 1c. Finally, amplitude or phase holograms can be used to create interference patterns between atomic wave functions, so that atoms are deposited on the substrate where the interference pattern is constructive, and no atoms are deposited at the surface where the interference pattern is destructive, as shown in Fig. 1d.

In addition to the processes shown in Fig. 1, it is also possible to simply take advantage of the direct-write feature of atom optics, using a material mask to shadow regions of the substrate during deposition. As a final note, we mention that with direct-writing, the eventual shape of the permanent structure that remains on the surface could in some cases depend strongly on interactions which occur after the atoms are deposited on the substrate. For example, depending on the atomic species and surface material, degree of surface con-

tamination, and ambient temperature, atoms can sometimes migrate across the surface after deposition, resulting in surface distributions which can be radically different from those originally induced by the light.

In the next section we begin by discussing some general principles of the manipulation of atoms by light, and then we discuss some of the history of atom optics applications. In section 3 we discuss some of the current research as it relates directly to fabrication, and some future prospects.

2 Atomic manipulation

2.1 Fundamentals of the light force

We have mentioned how light can control the deposition of atoms onto a substrate by acting as a lens, a mask, a waveguide, or a hologram for the atoms. In order to understand how light can act in these ways, we will discuss how the interaction between an atom and light results in a force on the atom.

Traditionally, the force exerted by light on atoms is divided into two categories: (1) stimulated or coherent processes in which the energy of the atoms is conserved during the interaction; and (2) spontaneous or incoherent processes where the energy of the atom is not conserved.[2, 3] Most of the coherent processes lead to motion of the atoms that can be easily modeled using analogies with conventional optics. The incoherent processes, however, find no analogy in conventional optics. These processes can cool atoms, compressing their phase space distribution, something that cannot be accomplished by the conservative forces of conventional optics. Thus atomic beams can be simultaneously collimated and brightened. This is an important difference between atom optics and conventional optics.

Both coherent and incoherent forces can be explained by considering the interaction be-

tween the electric field associated with the light field, and the dipole moment induced in the atom by this electric field. Consider a simple model for the atom which consists of a massive positive charge at the origin surrounded by a circular cloud of very light negative charges. In the presence of an external electric field **E**, the positive and negative charges will be displaced from each other, resulting in a net dipole moment **p** for the atom, where **p** is proportional to **E** and can be written $\mathbf{p} = \alpha\,\mathbf{E}$. The energy of the dipole in the field is then $-\mathbf{p}\cdot\mathbf{E}$. If the field is oscillating at a frequency ω, then the dipole moment will also oscillate at a frequency ω, though there will generally be some phase shift between the two oscillations. If, as is the case for light, the oscillations are very fast in comparison with the time scale for external motion, the relevant energy is not the instantaneous energy $-\mathbf{p}\cdot\mathbf{E}$, but the average of that energy over an optical cycle, i.e., $-|\mathbf{p}||\mathbf{E}|\cos\phi = -|\alpha||\mathbf{E}|^2\cos\phi \propto -|\alpha| I\cos\phi$, where I is the laser intensity and ϕ is the phase difference between the dipole and the field.

The stimulated or coherent force, which is sometimes also referred to as the dipole force, can be associated with the change in this average energy as a function of position, and hence arises from a gradient in the intensity. The sign of the force depends on the phase difference ϕ. If the field is detuned below resonance, ($\Delta < 0$, where Δ is the detuning of the laser from the transition), the phase difference is between 0 and 90° and $\cos\phi > 0$; therefore, if $\Delta < 0$ atoms are attracted to the intensity maxima. Conversely, for fields detuned above resonance, ϕ is between 90° and 180°, so $\cos\phi < 0$ and atoms are attracted to the intensity minima.

While the above derivation of the behavior of the stimulated force is essentially correct, it must be noted that there are a number of quantum mechanical subtleties that must be taken into account in order to properly model all phenomena. Discussion of these effects can be found, for example, in reference [4]. For the present we simply note that the stimulated force can also be described as the result of stimulated emission and absorption of photons, which

produces a coherent redistribution of photons among modes of the laser field. The force is considered coherent because the coherence of the atomic wavepacket is preserved during the interaction. In the limit of large detuning and/or low intensity, it can be shown that the potential associated with this force is given by

$$U = \frac{\hbar\gamma^2}{8\Delta}\frac{I}{I_s}, \tag{1}$$

where γ is the natural line width of the atomic transition (in rad/s), Δ is the detuning of the laser frequency from the atomic resonance (also in rad/s), I is the laser intensity, and I_s is the saturation intensity associated with the atomic transition. We note that U is sometimes expressed in terms of the Rabi frequency $\Omega = \gamma\sqrt{I/2I_s}$ as $U = \hbar\Omega^2/4\Delta$. For smaller detunings, and higher intensities, the potential can be written as

$$U = \frac{\hbar\Delta}{2}\ln(1+p), \tag{2}$$

where

$$p = \frac{I}{I_s}\frac{\gamma^2}{\gamma^2+4\Delta^2}. \tag{3}$$

This expression is valid provided the atom moves slowly enough in a spatially varying field to maintain equilibrium between its internal and external degrees of freedom. If this is not the case, velocity-dependent forces arise and the motion of the atoms can no longer be derived from a conservative potential.

The spontaneous or incoherent force cannot easily be associated with a change in energy as a function of position, although it also results from the induced atomic dipole. The incoherent force results from the induced dipole moment which is in quadrature with the electric field, and results in a force proportional the the gradient of the *phase* of the field, rather than the gradient of the intensity. This results in a net push in the direction of propagation of the

field. The spontaneous force is non-conservative and can therefore result in compression in phase space. For example, a geometry where two weak counter-propagating traveling wave fields are detuned below resonance results in very strong cooling, and is referred to as optical molasses. From a quantum mechanical point of view, this force can be viewed as the result of a stimulated absorption followed by a spontaneous emission. The force is considered incoherent because the coherence of the atomic wavepacket is not preserved during the interaction. In addition, the spontaneous emission occurs in a random direction, so there is a heating process associated with this force, even when the net average force results in cooling.

2.2 First approaches to atom focusing with lasers

The first atom optics element to be demonstrated was the single thick lens. In this experiment, Bjorkholm *et al*[5] focused an atomic beam using the stimulated force generated by a strong traveling wave field with a Gaussian intensity distribution $I \propto \exp(-2r^2/\sigma^2)$, where σ is the $1/e^2$ radius of the laser beam, which was about 100 μm. The laser field was detuned below resonance, so the potential minimum was at the intensity maximum. The researchers allowed an atomic beam of atoms to copropagate with the light, and showed that the atomic beam was focused by the light to a spot approximately 200 μm in diameter. The lens is considered thick because the atomic position changed significantly during the time that the atoms interacted with the lens.

Another type of lens, making use of the spontaneous force, was demonstrated by Balykin *et al.*[6]. In this configuration, four diverging laser beams were incident transversely upon an atomic beam. The laser beams were tuned exactly on resonance with the atoms, so a spontaneous force was exerted in the direction of the light propagation. Since the beams

were diverging, the light intensity, and hence the force, increased as a function of distance away from the beam axis, resulting in a lensing effect. Both concentration of an atom beam into a point and imaging of a two-slit atomic beam source were observed with this lens.

In 1992, focusing of an atomic beam by a large-period standing wave was observed by Sleator *et al*[7]. This experiment consisted of passing a beam of metastable helium atoms through a laser beam ($\lambda = 1.083\mu$m) that was reflected at grazing incidence from a glass surface. The optical standing wave that resulted from this grazing reflection had a period of about 45 μm, and the atoms were apertured to 25 μm, so all the atoms passed though a single period of the light field. The intensity variation within this single period resulted in a dipole force potential that formed a lens for the atoms. Imaging at a magnification of unity of both a single 2 μm slit and a 8 μm-period grating were observed with this lens.

The first suggestion that lasers could be used to focus atoms into the nanometer regime was made by Balykin and Letokhov[8], who proposed that a focused TEM^*_{01} ("doughnut"-mode) laser beam with atoms propagating axially would be a particularly good arrangement for this. Further analysis by Gallatin and Gould[9] and McClelland and Scheinfein[10] showed that indeed, even considering all the possible aberrations, spot sizes of a few nanometers could be expected.

2.3 Lens arrays, channeling and optical lattices

Another important development in atom optics has been the lens array[11]. In the experiments discussed above, the light produced a single positive or negative lens for atoms, which focused the atoms into a single spot. It is also possible to use light to produce an array of lenses. These lenses can simultaneously focus atoms into arrays of lines or dots. This allows parallel lithography over large areas, which is a key factor in making atom optics a

desirable approach for fabrication.

A simple example of a lens array is the array of parallel cylindrical lenses which can be generated using a standing-wave field. Consider an optical standing wave formed by two counter-propagating traveling plane waves with wave vectors $\pm k$ along $\hat{x}$. The x-dependence of the intensity is then given by $I = I_o \cos^2(kx)$, which results in a potential proportional to $\cos^2(kx)$ for positive detuning. Let this standing wave interact with an atomic beam propagating in the $\hat{z}$-direction. The force associated with the potential variation in x will tend to focus the atoms into a series of lines along potential minima, which are at the nodes of the standing wave, found at $kx = (2n + 1)\pi/2$, where n is an integer.

Thus, the plane standing wave will act like an array of cylindrical lenses focusing a plane wave of atoms into a series of parallel lines. It is important to note that each of the lenses in the array is separated from each other lens by a distance which is an exact half integral multiple of the atomic wavelength, which means that the resulting atomic distributions have excellent registration.

The discussion above describes the case where the plane wave forms a thin lens array, so that the atoms do not move significantly during the interaction. Most of the early experiments were done in the opposite limit where the atoms interacted with the lenses for a long time and were "channeled," that is, periodically focused and defocused as they passed through the lens array. The conventional optical analogy would be an array of graded index lenses, which could also be considered a waveguide.

The wave-guiding or channeling associated with atomic motion in thick cylindrical lens arrays was observed using spectroscopic techniques: Prentiss and Ezekiel[12] observed the distortion in the fluorescence due to atomic motion, and Salomon *et al.*[13] measured the distortion in absorption from a weak probe. The channeling was also demonstrated more

directly by Balykin *et al.*[14] who showed that the atoms could be gently guided around curves.

The atomic waveguiding discussed above is analogous to the guiding of light by a multimode fiber or waveguide, where the initial atomic distribution includes many eigenmodes of the waveguide. It is also possible to do experiments in a regime where only one or two of the lowest waveguide modes are populated. An array of these waveguides are used to form an optical lattice. This is potentially good for lithography because these low order modes can be very well separated spatially allowing for deposition of well separated features with little or no background, whereas the multimode waveguides discussed above can have a significant background connecting the features. In the following we will discuss how these lowest order modes can be very efficiently populated.

As mentioned in section 2.1 above, one of the important differences between conventional optics and atom optics is that in atom optics it is possible to make use of the spontaneous force to cool atoms and compress them in phase space. In the channeling experiments described above, a planar optical standing wave acted as an array of thick cylindrical graded index lens which periodically focused and defocused an atomic beam. Atoms are originally distributed uniformly in the potential and always have the opportunity to return to their initial value in the potential. Adding cooling to the potential allows the motion of the atoms in the wells to be damped so that they are eventually confined to a small region near the bottom of the potential wells, even if they started at a potential energy much higher than the potential minimum. The potential wells are periodically spaced and separated by half an optical wavelength, with spacings as small as a quarter of a wavelength possible in some geometries. Experiments which observe simultaneous cooling and channeling have been done in 1, 2, and 3 dimensions[15, 16, 17, 18, 19, 20, 21]. Indirect spectroscopic measure-

ments indicate that the atoms have been confined to within approximately $\lambda/20$ in diameter. The remaining regions of space are not populated, and the resulting distributions are often described as "optical crystals".

2.4 Atom mirrors as masks

In the sections above we discussed early experiments which showed that light can form lens arrays or waveguides that can control atomic deposition. In this section, we will discuss early experiments that showed that light can be used as a mask to selectively prevent deposition. Basically, a light field detuned above resonance can form a potential barrier which will reflect atoms back in their initial direction of propagation. If such a light field is present above a substrate, there will be no deposition onto the substrate in the regions where the light is present. Thus a patterned light field detuned above resonance will act as a mask which prevents deposition in regions where the light is present, and allows deposition in regions without light.

The early experiments discuss atom mirrors or "trampolines" rather than atom masks because they were more interested in the atoms which bounced off the light than in those that hit the surface. Consider light field with an intensity be given by $I = I_o \exp(-\alpha z)$, for $z > 0$. An atom of mass m will bounce off the light if it has a velocity v_z such that $\frac{1}{2}mv_z^2$ is less than the potential barrier due to the light. This atom will then freely propagate with velocity $-v_z$. This was first demonstrated by Balykin[22], who created the appropriate intensity dependence by using internal reflection from a prism. Similar experiments have since been done by other groups [23, 24], who used curved prism surfaces to make a focusing mirror for the atoms, and have enhanced the reflection by coating the prism with a dielectric cavity which enhances the intensity of the light at the surface to almost 1000 times

the initial intensity.

2.5 Diffraction of atoms from a laser beam or a microfabricated grating

In the sections above we discussed early experiments which showed that light can act as a lens array or a mask which controls atomic deposition. These experiments can be described by analogy with classic geometric optics, or ray tracing where the atom can be modeled as a billiard ball. This is not unreasonable since the typical De Broglie wavelength of the atoms is 0.01 nm. In the following section we will consider experiments where the wave-like nature of the atoms is important, so the billiard ball model will not give correct results. In particular, we will discuss experiments which demonstrated that the atomic wave function can be modified by phase and amplitude gratings, creating atomic interference patterns that can also be used to control deposition onto a substrate.

A series of pioneering experiments have been done which used the diffraction from phase and amplitude holograms to produce atomic interference patterns. In the first experiment Gould *et al.*[25] used the potential energy associated with an optical standing wave to produce periodic variation on the phase of an atomic wavepacket. Thus, the light acted as a phase grating for the atoms. The grating produced an atomic distribution with a 300 nm period. The period of the pattern was independent of the intensity of the standing wave, but the intensity did control the depth of the phase modulation and thus the amplitude of various orders of the diffraction pattern. Later, Ekstrom *et al.*[26]from the same group did an experiment with an amplitude hologram composed of a matter grating with a 200 nm period. This grating produced an interference pattern with a 100 nm period. Any of these diffraction patterns could have been deposited onto a substrate, creating periodic arrays of lines.

Atomic diffraction effects can also be used to focus atomic beams. Carnal *et al.*[27]

demonstrated this by focusing a beam of metastable helium atoms with a microfabricated Fresnel zone plate with diameter 210 μm and innermost zone diameter 18.76 μm. They showed that a 10 μm source of atoms could be imaged to a spot with diameter 18 μm, and also that the image of a double slit with width 22 μm and spacing 49 μm could be clearly resolved.

3 Current research in nanofabrication with atom optics

While a fairly broad range of atom manipulation techniques has been evolving over the past decade or so and possibilities for fabrication have been suggested, actual demonstration of the fabrication of nanostructures has only recently begun to appear. To date, efforts have concentrated mainly on the standing-wave lens array, in which a standing-wave laser field is used to focus atoms into a series of nanometer-scale lines as they deposit onto a surface (see Fig. 2). The standing wave is directed across the surface of the substrate, usually as close as possible, and atoms are focused by a stimulated, or dipole force that concentrates them into the nodes. This configuration has a number of important advantages for surface fabrication of structures. A laser standing wave by nature consists of very small features, of order the wavelength of light, which repeat with extreme regularity. Thus small scale as well as massive parallelism are built into the process from the beginning. Furthermore, the geometry allows for easy arrangement of the laser and atomic beams; many other configurations, such as focusing in a "doughnut"-mode laser beam[8, 9, 10], require making the atoms and the laser coaxial, which could pose practical challenges.

3.1 Sodium

In a pioneering experiment using the standing-wave configuration, Timp *et al.*[11] were able to deposit an array of lines of sodium atoms, forming a grating on a silicon substrate. The grating covered an area of about 0.2 cm^2, and had a pitch of 294.3 ± 0.3 nm.

The manipulation and focusing of the sodium atoms proceeded in two stages in this experiment (see Fig. 3). The initially uncollimated atom beam emerging from an effusive oven was first collimated using a region of laser cooling with optical molasses to cool the beam transversely from two sides. This was achieved by illuminating the beam transversely with circularly-polarized light from a CW single-frequency, stabilized ring-dye laser tuned slightly below the sodium D_2-line at 589.0 nm. An additional beam, shifted in frequency by 1.7 GHz, was combined with this beam to repump those atoms which had fallen into the $F = 1$ ground-state hyperfine level. The collimation of the atomic beam with optical molasses was necessary to reduce the transverse kinetic energy of the atoms to the level at which their trajectories could be significantly modified by the standing wave potential, which had a depth of about 1 μeV.

After collimation, the atom beam passed through a standing wave positioned very close to the substrate. This laser beam was also circularly polarized, and also had a small 1.7 GHz-shifted repumping component. Its main frequency was shifted by 60–140 MHz relative to the atomic line so that there would be little excited-state population, and hence little possibility for spontaneous emission and the associated velocity-dependent forces. Both positive and negative detunings were tested, and both gave comparable results, though in one case the atoms were attracted to the nodes (positive detuning) and in the other they were attracted to the antinodes (negative detuning).

An important component of this experiment was ensuring that the standing-wave nodes

did not move relative to the substrate on which the atoms were being deposited, as this would result in a smearing of the pattern. Since the node positions are determined solely by the position of the surface of the standing-wave mirror, it was necessary to stabilize this mirror relative to the substrate. This was done by forming an optical cavity between a small mirror on the sample mount and the standing wave mirror. Using standard optical cavity-locking techniques, it was possible to monitor the transmission of this cavity and servo the position of the standing-wave mirror, keeping it in registry with the substrate within $\lambda/45$, or 13 nm.

The sodium gratings were observed while under vacuum by illuminating them with a laser beam with a wavelength between 560 and 580 nm. Diffraction was observed, and the periodicity of the grating was inferred from the diffraction angle. A number of detunings and laser powers were used, and each resulted in a grating with the expected pitch of $\lambda/2 =$ 294.5 nm within an uncertainty of 0.4 nm.

3.2 Chromium

The experiments on sodium were closely followed by work reported by McClelland *et al.*[28], in which chromium atoms were focused into an array of lines on a substrate using a laser standing wave. With chromium substituted for sodium, two important advances were possible. The deposited structures could be removed from vacuum for direct examination with a variety of microscopy techniques, and for the first time applications involving a hard, ultra-high vacuum compatible material with many useful properties could be envisioned.

As with sodium, the chromium experiments consisted of an effusive atomic beam that was first collimated in a region of optical molasses and then focused into a series of lines by a standing wave grazing along the surface of a silicon wafer. The laser wavelength used in this case was 425.43 nm, which corresponds to the $4s(^7S_3) \rightarrow 4p(^7P_4^o)$ transition in the chromium

atom, and no additional laser frequencies were required because the predominant isotope of chromium (^{52}Cr at 84%) has no hyperfine structure. The optical molasses for the chromium atoms was set up in a polarization-gradient configuration[30], in order to achieve a sub-Doppler transverse kinetic energy spread. In a simplification of the substrate mount, the silicon wafer was held in direct contact with the standing-wave mirror, which was mounted in the vacuum. This provided registry between the standing wave and the substrate to within a few nanometers without the need for active stabilization.

Because chromium forms a very thin ($\sim$1 nm) layer of very tough, passive oxide when exposed to air, the chromium lines formed by laser-focused deposition could be removed from the vacuum and imaged in air with atomic force microscopy (AFM), or examined by scanning electron microscopy (SEM). Fig. 4 shows an AFM image of a 2 μm by 2 μm section of the lines, which cover a 0.4 mm by 1 mm region of the substrate. Fig. 5 shows an SEM image of the lines with a larger field of view, illustrating their uniformity[29].

The lines on the substrate whose image is shown in Fig. 4 had an average line width of 65$\pm$6 nm (full-width at half-maximum), a pitch of 212.78 nm, and an average height of approximately 20 nm. The width of the lines depends on details of the deposition, such as the degree of collimation and velocity spread of the atomic beam, and the laser beam power, detuning and waist size. The pitch of the lines was not measured directly, but rather inferred from the known wavelength of the laser light. Because of the geometry of the experiment, the pitch of the lines must be equal to the periodicity of the standing wave, i.e., half the laser wavelength, with very small corrections (of order parts per million). The height of the lines was of course dependent on the length of the deposition, which was 20 minutes in the case of Fig. 4.

standard uncertainty ?
how determined ?

3.3 Aluminum

While chromium has a number of potentially useful applications, such as nanowires, etch resists, and structured magnetic materials, other materials are also worth pursuing for atom-optical applications. Very recently McGowan and Lee[31] have reported one-dimensional laser cooling of an aluminum atomic beam, which is the first step toward performing laser focusing in a standing wave for this atom. The advantages of laser focusing aluminum are twofold: aluminum is currently the material of choice for interconnects in microcircuits, so it is a desirable atom to manipulate, and the wavelength of the laser used is shorter than in the case of sodium or chromium, so the resolution is potentially higher. For this experiment the laser was tuned near the $3p(^2P^o_{3/2}) \rightarrow 3d(^2D_{5/2})$ transition in atomic aluminum, which has a wavelength of 309.3 nm. The UV laser light was produced by frequency doubling of a CW dye laser in an external build-up cavity. While the $3p(^2P^o_{3/2})$ state is not the ground state of aluminum, it is sufficiently low-lying to be thermally populated by roughly 20% of the atoms emerging from the atomic oven. Significant Doppler cooling of the atomic beam was observed, and work is now underway to deposit structures using a standing wave.

3.4 Modeling of the process

Along with the experiments described above, there has also been work done on understanding the behavior of laser focusing in a standing wave from the point of view of being able to predict the line shape of deposited structures and hence the ultimate resolution of the process. Berggren *et al.*[32] and McClelland[33] have taken a semiclassical approach, solving the equation of motion of the atoms as they pass through a single node of the standing wave assuming a conservative potential given by the light shift induced by the laser. Any effects due to quantization of the atomic motion are ignored in this approach, mainly because these

efects are small for a wide range of parameters. The advantage of this approach is that rays can be traced rather simply and the influence of experimental parameters can be explored.

One outcome of this work has been the realization that the standing wave node can act as a true lens, and focal lengths and aberrations can be discussed in complete analogy to optics, in particular particle optics. For example, McClelland[33] has shown that the essential behavior of the lens is governed by a single parameter a, given by

$$a = \frac{\hbar\Delta}{2E_0}\frac{I}{I_0}\frac{\gamma^2}{\gamma^2+4\Delta^2}k^2\sigma_z^2, \tag{4}$$

where Δ is the laser detuning from the atomic resonance, E_0 is the kinetic energy of the atoms, $k = 2\pi/\lambda$ (λ being the atomic wavelength), σ_z is the $1/e^2$ radius of the laser beam, I is the laser intensity, I_0 is the saturation intensity of the atomic transition, and γ is the atomic line width. In the paraxial, thin-lens limit of a weak lens, the focal length is simply given by

$$f = \sqrt{2/\pi}\,\sigma_z/a. \tag{5}$$

When the lens is thick, such as when the substrate plane is within the laser beam, the focal length and principal plane location are still entirely determined by a, though a numerical calculation must be carried out to obtain the dependence. These parameters scale with σ_z, so once the numerical calculation is done, the results can be used to predict the behavior of any lens.

A cewntral result of the semiclassical calculations is that line widths of order ten nanometers are possible with a thermal atomic beam having sub-Doppler-cooled transverse velocity spread. This is generally borne out in the experiments so far; however sufficient discrepancies still exist, suggesting that further theoretical work is needed. Along these lines, Marksteiner *et al.*[34] have performed general quantum calculations of the localization (or quantum "squeezing") of atoms in a standing wave potential. While no numerical comparisons

can be made at present, this is clearly an area where fruitful comparisons can be made to enhance our understanding of the role played by quantum and non-adiabatic effects in the focusing of atoms in a standing wave.

4 Future prospects

In the research that has been performed so far, it has been clearly demonstrated that nanometer-scale patterns can be made on a surface by utilizing the techniques of atom optics. The new approaches introduced by these techniques, with the associated improvement in resolution and parallelism, could have a very significant impact on the field of nanostructure fabrication. Atom optics, however, is in its infancy, and the extent of its impact on nanostructure fabrication depends on progress in two broad areas: (a) the techniques should be extended to allow working with as many different materials as possible, especially those of interest to specific applications, and (b) methods should be devised to allow the possibility of fabricating more general patterns. Already, a number of possible approaches are being discussed to overcome these hurdles, and it is expected that many new developments will be forthcoming in the near future.

4.1 Other materials

One way that atom optics can be extended to other materials is simply to follow the approach taken already to some extent, i.e., look for appropriate atomic transitions and the associated lasers in the species of interest. The requirements can be somewhat stringent in this case, but nevertheless it has led to the introduction of chromium and aluminum as candidates. For an atomic species to be considered for atom optics, it must first of all have a transition that is accessible with a CW, single-frequency laser with enough power to saturate the transition.

This transition must originate in the ground state of the atom, or in a state that has enough population such that most or all of the atoms are affected. In this regard the atomic beam must not have too high a concentration of other isotopes, dimers, ions or excited species. Second, if an optical molasses stage is necessary for collimation, then it is necessary for the atomic transition to be a cycling one; that is, atoms excited by the laser must return to the same state so that they can repeatedly absorb photons. Sometimes the cycling requirement is difficult to meet because atoms have hyperfine structure or other complicated level structure. This difficulty can often be overcome, however, by the introduction of other laser frequencies, as in the case of sodium. While all these requirements seem rather restrictive, it is still quite possible that atom optics techniques will be applied to new species in the future. Laser technology is constantly improving, and as new CW tunable sources emerge, additional atomic species will probably become accessible to atom optics.

Another perhaps more fruitful approach to generalizing the applicability of atom optics is to make use of some sort of pattern-transfer mechanism. In this approach, a pattern is generated with an atomic species that is compatible with atom optical techniques, and then the pattern is transferred to the desired material by some sort of etching process. At present, two possible routes exist toward this; in the future, other possibilities may evolve.

The first technique involves making use of the etch resist properties of chromium. For example, if a pattern in gold is desired, an atom-optically generated pattern of chromium can be deposited on the surface, and then the sample is etched in a solution of KCN. The chromium prevents the gold from being etched and the pattern is transferred to the gold. If desired, the chromium can then be removed with HCl or commercial chrome etch. Dry, or reactive-ion etching can also be used in a similar way to transfer the pattern to GaAs or other materials, because chromium provides excellent resistance to most of these etch

processes.[35]

The second technique uses a resist layer to transfer the pattern. The resist might be one of the standard high resolution electron-beam resists used for conventional lithography, or it could consist of a thiol or siloxane-based self-assembled monolayer (SAM). SAM-based resists offer some unique advantages, promising very high sensitivity and resolution. The desired material is coated with the resist, and then the resist is exposed by an atom-optically focused pattern of atoms. Subsequent etching transfers the pattern to the substrate.

Exposure of the resist can occur either through a chemical or an energetic mechanism. In the first case, a reactive atom such as one of the alkalis (all of which can be used for atom optics) strikes the surface and reacts with the resist, making it susceptible to removal by a solvent or etch. In the second, metastable rare-gas atoms (again, all accessible to atom optics) strike the surface and liberate their internal energy in a shower of secondary electrons that can go on to damage the resist and render it soluble or no longer resistant to an etch. Preliminary investigations on both of these processes have indicated that they are real possibilities and should be pursued further.

4.2 More general patterns

While atom optics has been shown to have the potential for very high resolution and massive parallelism, a pattern more complicated than a grating has yet to be demonstrated. Before discussing approaches to the general pattern problem, however, it should be noted that simple one-dimensional atom-optically generated artifacts have already found a unique, critical application. As discussed above, the pitch of the gratings fabricated in a standing wave can be directly derived from the wavelength of the laser light. Since the laser light is locked to a well-known atomic transition, the pitch is traceable through the speed of light in vacuum

to a well-characterized frequency. Thus the grating can be used as a length standard on the nanometer scale, a regime where accurate calibration artifacts are sorely needed.

But in order to explore the full range of possibilities for atom-optical nanofabrication, it is useful to contemplate the extension of the techniques to more general patterns. A number of concepts are being discussed, and these range from simple extensions of current techniques to whole new concepts.

Perhaps the simplest generalization of a one-dimensional deposition experiment involves adding another standing wave perpendicular to the first one, so that a two-dimensional pattern is deposited. In this case a pattern of dots with spacing $\lambda/2$ can be produced. These dots could already be useful for the fabrication of a quantum dot array, or a patterned magnetic medium. However, if the dots can be made with sufficiently small size, i.e. 10-20 nm, then the possibility exists for scanning the substrate within the unit cell of the array as they deposit, thereby "painting" a pattern of any desired shape. Because of the natural periodicity of the standing wave, this pattern would be reproduced precisely in each well of the standing wave across the entire substrate. The result would be the massively parallel fabrication of an arbitrary structure, with obvious implications for device applications.

Another approach to generalizing the pattern concerns cases when the periodicity of the standing wave is too high, i.e., when the dots or lines are too close together. In this situation, one can imagine arranging a mask in registry with the standing wave that allows atoms to deposit only in certain areas. The mask needs only to be fabricated with a resolution corresponding to $\lambda/2$, or a few hundred nanometers, that is, just enough to select the desired periods of the standing wave. Once the atoms enter the standing wave, they are focused to the limits of atom optics, i.e., of order 10 nm.

Even more general patterns can in principle be created by recognizing that a standing

wave is only a very simple example of what is essentially a broad continuum of possible intensity patterns that can be generated on a surface. The challenge of this approach is to decide on the desired pattern, and then design an optical field that will concentrate atoms into this pattern using our knowledge of atom optics. In order to take advantage of the small sizes (or high spatial frequencies) attainable with optical fields, it is probably most fruitful to consider patterns that can be made as a result of some form of interference. The standing wave is the simplest example of such a pattern, but far more complicated ones are possible when more beams from other directions with controllable phase are introduced. While there are some limitations on what optical fields can be generated because of the laws of diffraction and the need to use only a single wavelength, a wide range of patterns are still possible.

At present, it is difficult to predict in what exact form atom optics could prove the most useful for nanolithography, although it is clear that a large variety of possibilities exist for the future. Eventually, any or all of the possible porcesses outlined in Fig. 1, from masks to lenses to waveguides to atom holograms, may break some fundamental barriers in the ongoing search for new ways to fabricate with increasingly smaller dimensions at ever higher efficiency.

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Figures

Figure 1. Atom optics as a tool for nanofabrication.

Figure 2. Focusing of atoms in a standing wave laser field.

Figure 3. Experimental apparatus for focusing sodium atoms with a standing wave into a grating with 294 nm pitch (Ref. [11]).

Figure 4. Atomic force microscope image of chromium lines created by focusing chromium

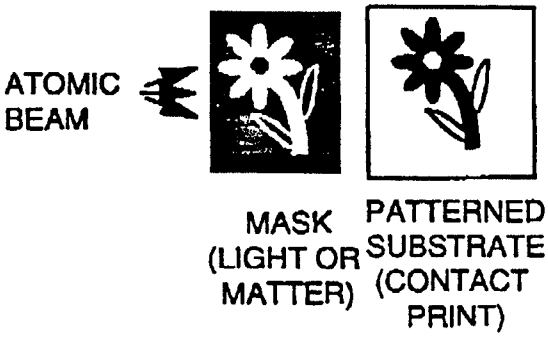
atoms in a standing wave (Ref. [28]).

Figure 5. - Scanning electron microscope image of chromium lines created by focusing chromium atoms in a standing wave (Ref. [29]).

(a)

MASKS

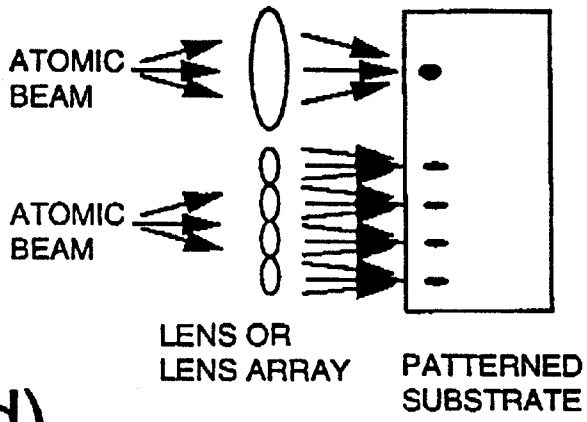
- A Mask Can Be Used to Prevent Atoms From Hitting the Surface



(b)

LENSES AND LENS ARRAYS

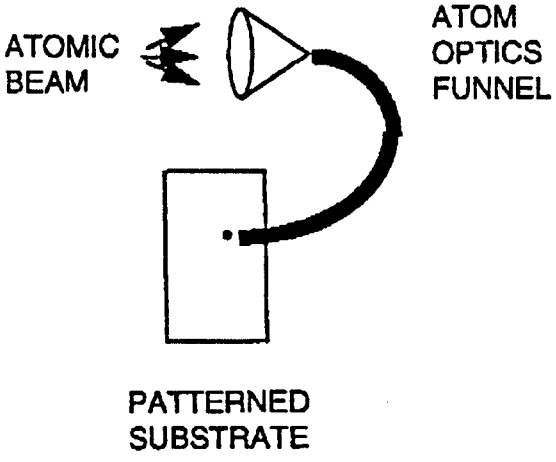
- A Lens or Array of Lenses Can Focus Atoms Onto the Substrate
- Images << Lens Size



(c)

WAVEGUIDES

- Act Like Optical Fiberor Fiber Bundle
- Image Is Same Size As Core



(d)

PHASEAND AMPLITUDE GRATINGS

- Atomic Beams Can Interfere With Themselves
- Short Atom Wavelength Offers High Resolution in Atom Holograms

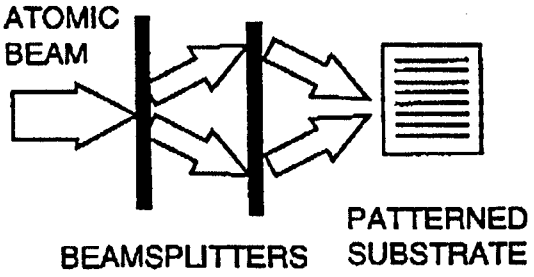


FIG 1

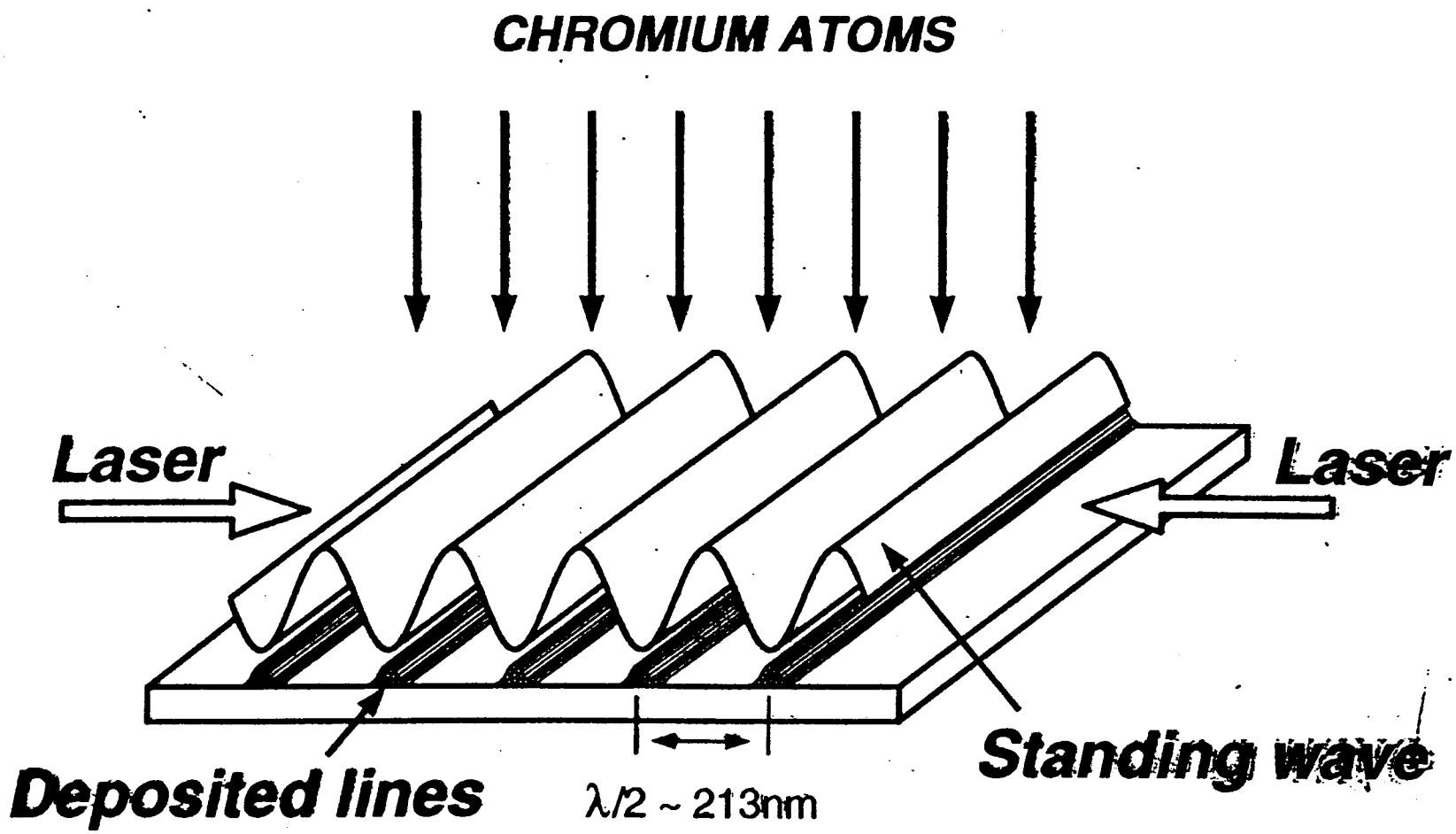

CHROMIUM ATOMS
Laser
Laser
Deposited lines
λ/2 ~ 213nm
Standing wave

FIG 2.

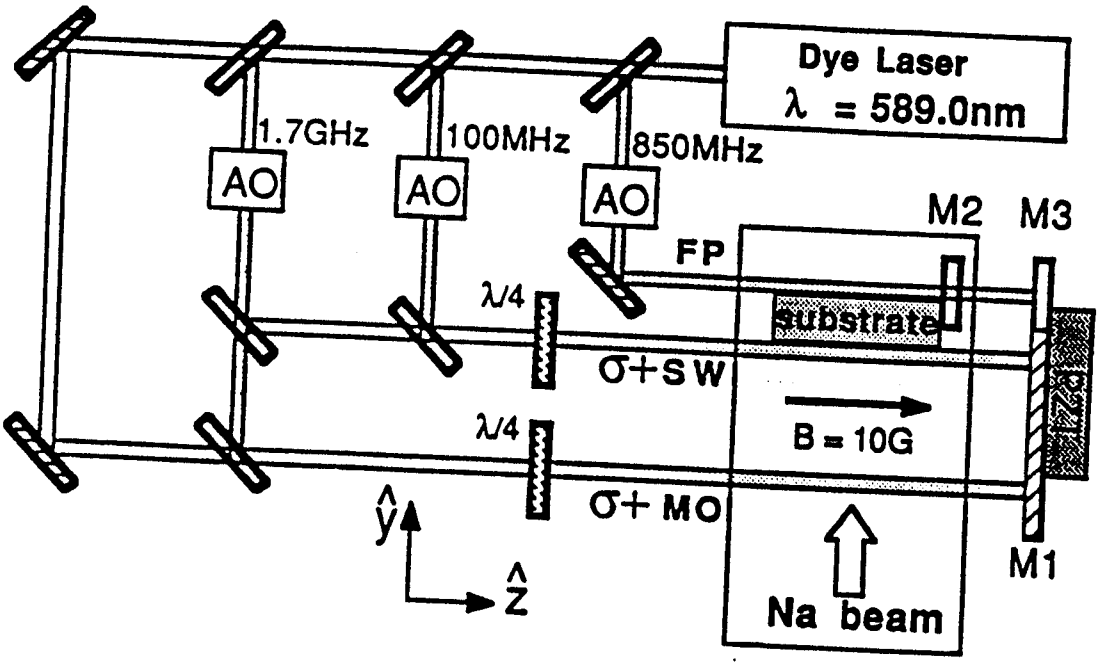

Dye Laser
λ = 589.0nm
1.7GHz
100MHz
850MHz
AO
AO
AO
M2
M3
FP
λ/4
substrate
σ+SW
λ/4
B = 10G
σ+ MO
M1
ŷ
ẑ
Na beam

FIG 3

Fig2

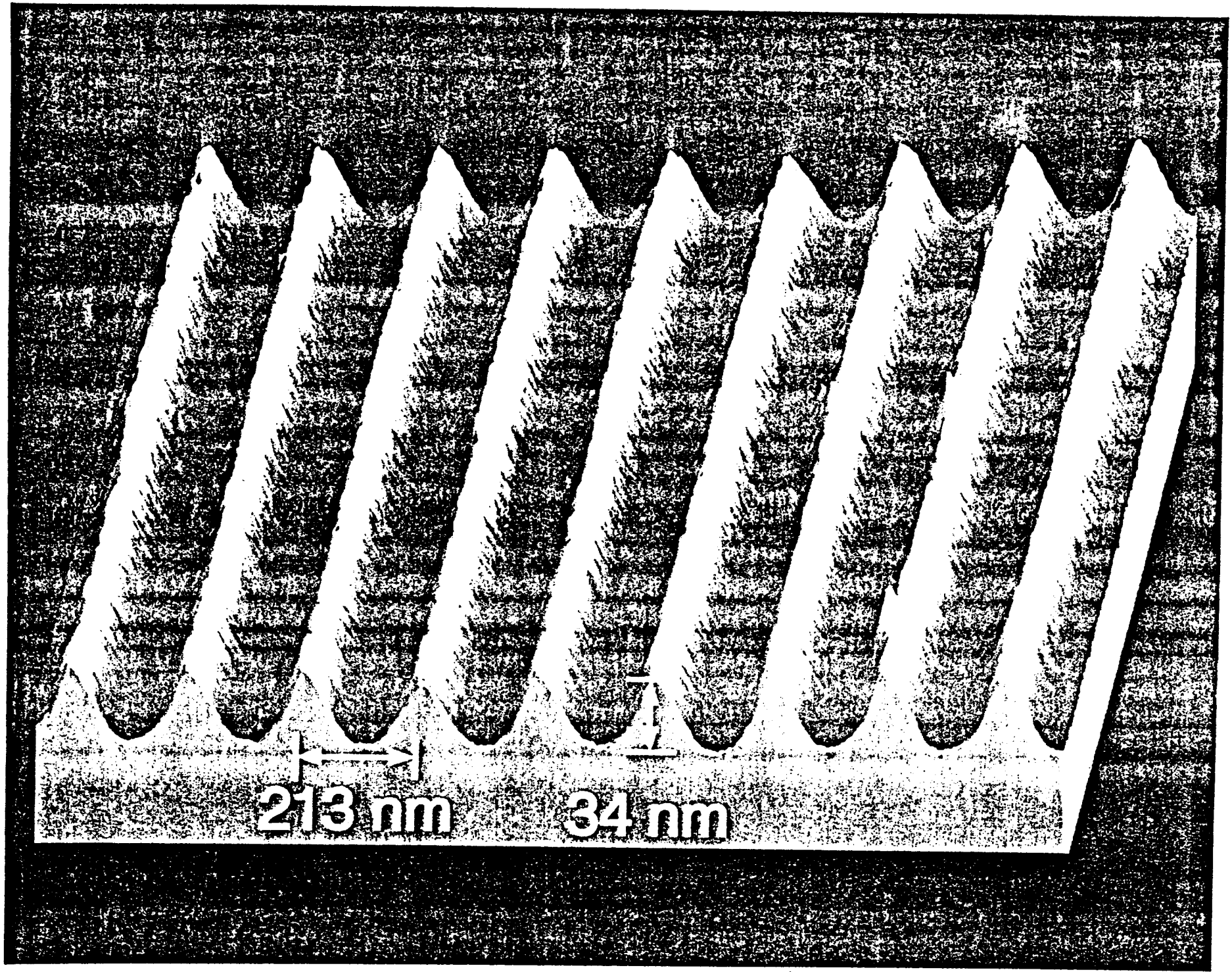


FIG 4

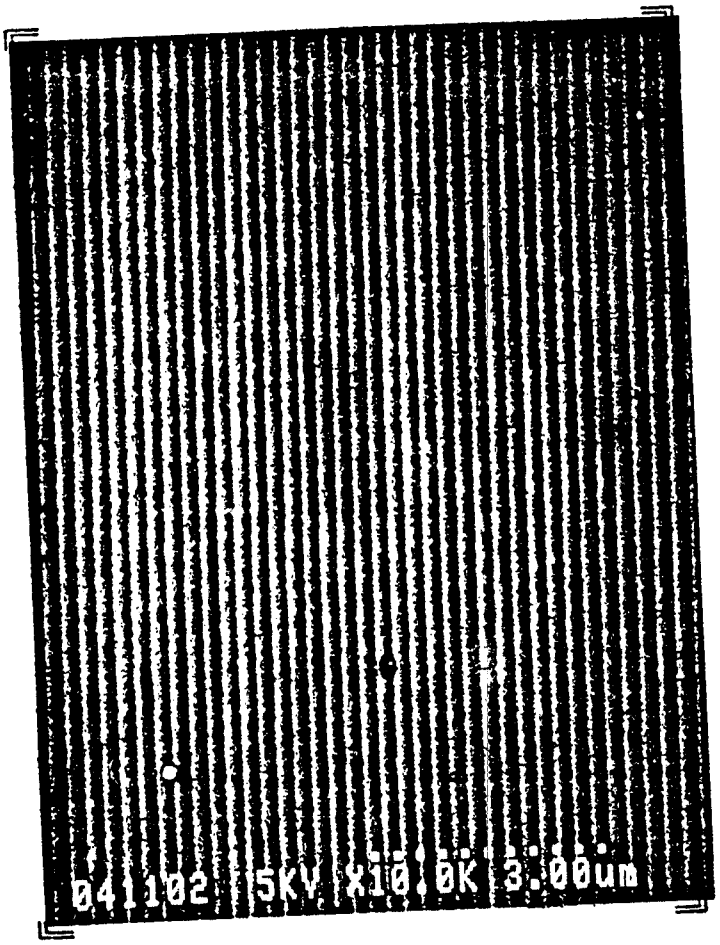


FIG 5